

# The accretion engine in pre Main Sequence stars and its role in the evolution of young planetary disks

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## ABSTRACT

*Planetary systems are angular momentum reservoirs  
generated during star formation*

Powerful outflows are known to regulate angular momentum transport during star formation. Elementary physical considerations show that, to be efficient, the acceleration region for the outflows must be located close to the star (within 1 AU) where the gravitational field is strong. According to recent numerical simulations, this is also the region where terrestrial planets could form after 1 Myr. The temperature of the accretion-outflow engine is between 3000 K and 300,000 K. After 1 Myr, during the classical T Tauri stage, extinction is small and the engine becomes naked and can be observed at ultraviolet wavelengths. Understanding the physics of this engine is of prime importance to understand our own Sun and the source of its magnetic activity.

*Key words:* UV astronomy, pre-main sequence stars, jets, winds, young planetary disks

## 1. Introduction

Understanding how stars form out of the contracting cores of molecular gas is a major challenge for contemporary astrophysics. Angular momentum must be conserved during gravitational contraction and magnetic flux is built up and dissipated in the

process, but the underlying mechanisms are still under debate. Solar-like protostars are an excellent laboratory for this purpose since their pre-main sequence (PMS) phases last  $\sim 100$  Myr. The collapse of low-mass protostars is subalfvénic, thus these protostars are expected to be magnetized. The detection of kG fields in stars as young as a few million years (Guenter et al. 1999; Johns-Krull et al. 1999) supports this assumption.

Star growth is regulated by the interaction between the stellar magnetic field and the disk. The physics of this interaction is outlined in Figure 3. The disk-star interaction basically transforms the angular momentum of the disk (differential rotation) into plasmoids that are ejected from the system. There is a current sheet that separates two distinct regions: an inner stellar outflow and an external disk flow. Magnetic flux dissipation should occur in the current layer producing the ejection of plasmoids, as well as the generation of high energy particles (cosmic rays), X-rays, and ultraviolet radiation. The phenomenon is non-stationary and is controlled by two different temporal scales: the rotation period and the magnetic field diffusion time scale. Stellar rotation is a well-known parameter that controls the opening of the field lines towards high latitudes. Plasmoid ejection, however, is controlled by field diffusion which is poorly determined (see *e.g.*, Priest & Forbes 2000). All models can be fitted into this basic configuration (Uzdensky 2004).

This process has been investigated by means of numerical simulations from the early works by Goodson et al (1997) till the last results (*i.e.* von Rekowski & Branderburg 2004). They show that the fundamental mechanism for jet formation is robust; numerical simulations with different parameters (disk/star fields) and initial conditions produce outflows that fit within the generic description sketched in Fig. 1. (see *i.e.* Matt et al. 2002). Despite the numerical advances made so far, the real properties of the engine are poorly known because of the lack of observations to constrain the modelling. Very important open questions include:

- (i) How does the accretion flow proceed from the disk to the star? Is there any preferred accretion geometry like, for instance, funnel flows?
- (ii) What roles do disk instabilities play in the whole accretion/outflow process?
- (iii) What are the dominant wind acceleration processes? What are the relevant time-scales for mass ejection?
- (iv) How does this high energy environment affect the chemical properties of the disk and planetary building?
- (v) How important is this mechanism when radiation pressure becomes significant as for Herbig Ae/Be stars?

Infrared and radio wavelengths cannot access the tiny spatial scales involved ( $< 0.1$  AU or  $0.7$  mas for the nearest star forming regions compared with ALMA's resolution of  $10$  mas) and the temperatures are too high ( $3000$ – $300,000$  K). The UV spectral range is the richest for diagnosing astrophysical plasmas in the  $3000$ – $300,000$  K

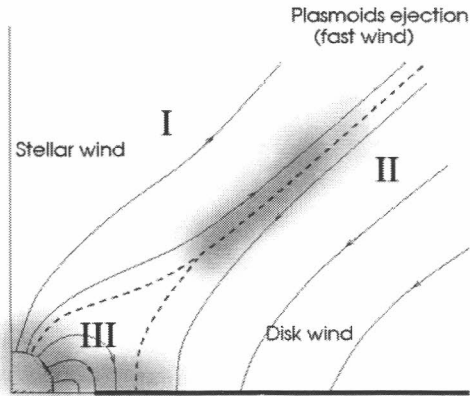


Figure 1: The interaction between the stellar magnetic field and the disk twists the stellar field lines due to the differential rotation. The toroidal magnetic field generated out of the poloidal flux and the associated pressure tends to push the field lines outwards, inflating them, and eventually braking the magnetic link between the star and the disk (boundary between regions I and II). Three basic regions can be defined: Region I dominated by the stellar wind, Region II dominated by the disk wind and Region III dominated by stellar magnetospheric phenomena. The dashed line traces the boundaries between this three regions. The continuous lines indicate the topology of the field and the shadowed areas represent regions where magnetic reconnection events are likely to occur, producing high energy radiation and particles (from Gómez de Castro 2004).

temperature range since the resonance lines of the most abundant species are located in the UV. In addition, as the UV radiation field is strong in the circumstellar environment, fluorescence emission from the most abundant molecules ( $\text{H}_2$ ,  $\text{CO}$ ,  $\text{OH}$ ,  $\text{CS}$ ,  $\text{S}_2$ ,  $\text{CO}_2^+$ ,  $\text{C}_2$ , and  $\text{CS}$ ) is observed. As a result, a single high-resolution spectrum in the 1200–1800 Å range provides information on the molecular content, the abundance of very reactive species such as the O I, and the warm and hot gas associated with the CTTs. The potential of UV spectroscopy for studying the physics of accretion during PMS evolution is outlined below.

## 2. Observation of the accretion engine in T Tauri stars

The engine is a small structure ( $\leq 0.1$  AU) with several different constituents (the accretion flow, stellar magnetosphere, winds, and inner part of the accretion disk) all radiating in the ultraviolet. The UV spectrum of the T Tauri Stars (TTs) has a weak continuum and many strong emission lines. The continuum is significantly stronger than that observed in main sequence stars of similar spectral types (G to M), as a result, the underlying photosphere is barely detected, and only in warm (G-type). This excess decreases as the stars approach the main sequence (see Fig. 2). Simple models of hydrogen free-free and free-bound emission added either to black bodies or to the spectra of standard stars reproduce the UV continuum reasonably well (Calvet et al. 1984; Bertout et al. 1988; Simon et al. 1990). The fits yield chromospheric-like electron temperatures of  $1\text{--}5 \times 10^4$  K. Three different mechanisms have been proposed to generate this hot plasma and its UV continuum: (1) a dense chromosphere (Calvet et al. 1984), (2) the release of the gravitational binding energy from the infalling material (Bertout et al. 1988; Simon et al. 1990; Gullbring et al. 2000), and (3) an outflow (Ferro-Fontán & Gómez de Castro 2003; Gómez de Castro & Ferro-Fontán 2005). This uncertainty in the formation of the UV emission points out why high-resolution UV spectroscopy and monitoring are so crucial for understanding and constraining the physics of the engine.

### 2.1. Accretion tracers

The most obvious signature of accretion is the detection of narrow red-shifted absorption components on top of the emission profiles of singly ionized species such as Mg II or Fe II with strong transitions in the UV at 2600Å and 2800Å. It is widely accepted that this absorption is produced in funnel flows: magnetic tubes connecting the inner disk to the stellar surface. Plasma within the funnel flows is expected to radiate over a broad range of temperature, from 3,000 K at the disk end to some 1 MK at the stellar surface. The kinetic energy of the infalling material is dumped into heating at the stellar surface; the temperature in the accretion shock may reach  $10^6$  K. The dominant output radiation is produced by the photoionized preshock infalling gas (Gómez de Castro & Lamzin 1999; Gullbring et al. 2000). However there are no detailed maps of the funnel flows except for some attempts made in the optical range (Petrov et al. 2001; Bouvier et al. 2003). UV mapping is crucial to determining the rigidity of the flux tubes and thus the possible distortions induced by differential rotation and the magnetic diffusivity of the disk. Thus the full accretion column could be tracked by monitoring CTTs with a high-spectral resolution UV instrument, but this observation has not yet been carried out! The only UV monitoring of CTTs was by the IUE satellite with low dispersion due to the small effective area of its 40 cm telescope. Nevertheless, the results are very promising as rotational modulation of the UV continuum and line fluxes were detected in DI Cep and BP Tau (Gómez de Castro & Fernández 1996; Gómez de Castro & Franqueira 1997a). This modulation



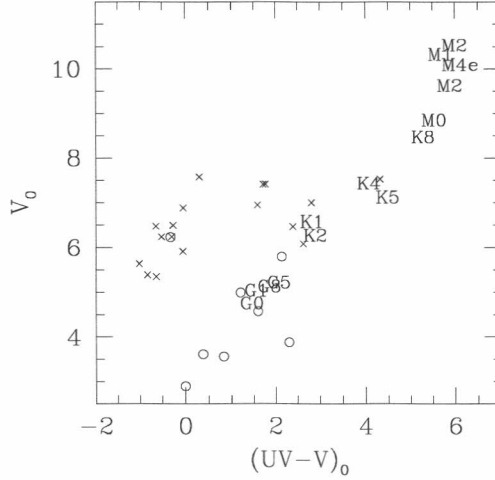


Figure 2: The  $(UV-V, V)$  colour – magnitude diagram for the T Tauri stars observed with the IUE satellite in the Taurus region (a distance of 140 pc to Taurus has been assumed). The crosses represent cool TTSs (spectral types later than  $\sim K3$ ) and the open circles warm TTSs (spectral types earlier than  $\sim K3$ ). The location of the main sequence is marked by the spectral types. The stars closer to the main sequence are the WTTSs (from Gómez de Castro 1997).

is caused by the small size of the accretion shock, which occupies only a small fraction of the stellar surface.

An important result of these campaigns is that only  $\sim 50\%$  of the UV continuum excess is rotationally modulated. Thus, a significant fraction of the UV excess is not produced by the accretion shock. Whether the wind or an extended magnetosphere is responsible for the UV continuum excess remains a matter of debate.

## 2.2. Disks tracers

High-resolution HST/STIS spectra have revealed, for the first time, the rich UV molecular emission in CTTS.  $H_2$  fluorescence emission has now been studied in detail in the nearest CTTS, TW Hya, and the richness of the spectrum is overwhelming: Herczeg et al. (2002) detected 146 Lyman-band  $H_2$  lines. The observed emission is likely produced in the inner accretion disk, as are the infrared CO and  $H_2O$  lines. Using this diagnostic technique, Herczeg et al. (2004) estimated that the warm disk surface has a column density of  $N_{H_2} = 3.2 \times 10^{18} \text{ cm}^{-2}$ , temperature of  $T = 2500 \text{ K}$ ,

and filling factor of  $H_2$  as seen from the source of the  $Ly\alpha$  emission of  $0.25 \pm 0.08$ . The observed spectrum shows that some ground electronic state  $H_2$  levels with excitation energies as large as 3.8 eV are pumped by  $Ly\alpha$ . These highly excited levels may be formed by dissociative recombination of  $H_3^+$ , which in turn may be formed by reactions involving X-rays and UV photons from the star. A quick inspection of the UV spectra in the IUE and HST archives shows that fluorescent  $H_2$  UV lines are observed in most of the TTSs (see also Gómez de Castro & Franqueira 1997b; Valenti et al. 2000; Ardila et al. 2002).

The role of far-UV radiation fields and high energy particles in the disk chemical equilibrium is now beginning to be understood. Bergin et al. (2003) showed how strong  $Ly\alpha$  emission may contribute to the observed enhancement of CN/HCN in the disk. The penetration of UV photons coming from the engine in a dusty disk could produce an important change in the chemical composition of the gas allowing the growth of large organic molecules. In this context, UV photons photodissociating organic molecules at  $\lambda > 1500 \text{ \AA}$  could play a key role in the chemistry of the inner regions of the disk, while those photodissociating  $H_2$  and CO will control the chemistry of the external layers of the disk directly exposed to the radiation from the central engine (see *e.g.*, Cernicharo 2004).

UV radiation interacting with the disk can be primary (direct UV radiation from the engine) or secondary (UV radiation generated in the energy cascade produced by the propagation of relativistic particles and hard X-ray photons within the disk). The effect of this secondary radiation needs to be studied (see Glassgold et al 2004 or Gómez de Castro & Antonucci, 2006 for evaluations). An important outcome would be the generation of a hot disk component associated with energetic photoelectrons. This component could be responsible of the strong far UV emission detected in the TTSs (Bergin et al. 2004).

### 2.3. Winds tracers

Outflows from TTSs are characterized by being collimated into a beam at large scales, this allows differencing the terminal from the acceleration regime. The acceleration regions is very small ( $< 0.1 \text{ AU}$ ) and cannot be spatially resolved thus TTSs spectra contain the contribution from the whole region and part of the terminal region. The collimated region or jet has been observed to extend up to scales of  $\sim 0.1 \text{ pc}$ . The terminal region is cooler and more diffuse than the acceleration region and thus the spectral tracers are different.

#### *Jets and Herbig-Haro Objects*

Since early in the IUE project, it has been known that protostellar jets and Herbig-Haro objects have a higher degree of ionization than previously inferred from optical data (Bohm-Vitense et al. 1982; Schwartz et al. 1985; see also Gómez de Castro & Robles 1999 for a compilation). High-excitation objects like HH1 or HH2 produce strong emission lines of C IV 1548, 1550  $\text{\AA}$ , OIII]

1664 Å, Si III] 1892 Å, and C III] 1909 Å (Ortolonai & D’Odorico 1980). However low-excitation objects like HH43 or HH47 are characterized by the presence of the H<sub>2</sub> Lyman band emission lines (Schwartz 1983). A detailed study of HH 29 combining optical and UV data led Liseau et al. (1996) to propose a two phase model with a warm component ( $T = 10^4$  K and  $n_e = 10^3$  cm<sup>-3</sup>) and a hot, dense component ( $T = 10^5$  K and  $n_e = 10^6$  cm<sup>-3</sup>) with a very small filling factor (0.1%–1%).

### *T Tauri stars*

The emission profiles of the Mg II resonance lines (2796, 2803 Å) show pronounced broad absorption in their blue wing for the 16 TTSs observed with IUE or HST (see *e.g.*, Gómez de Castro 1997). Blue-wing absorption is also observed in Ly $\alpha$ . Also, narrow and blueshifted C III] 1909 Å and Si III] 1892 Å emission has been detected at the same velocity as the optical jets in some TTSs (Gómez de Castro & Verdugo 2003a). This emission is produced at the base of the jet in scales <12 AU; wind temperatures of about 30,000 K have been derived from these data (Gómez de Castro & Verdugo 2003b). In other sources, the C IV, C III] and Si III] profiles are very complex with centroids shifted to bluewards shifted wavelengths and extended blue wings reaching  $\sim 300$  km s<sup>-1</sup>. This peculiar profiles indicate that the wind kinematics cannot be fitted to a simple expansion motion.

These data provide four key pieces of information: (i) there is a broad range of temperatures in the outflows (3,000–30,000 K), (ii) outflows are not spherically symmetric, and (iii) their kinematics produce line broadenings/asymmetries similar to the jet velocity (or terminal velocity of the outflow) in several sources, and (iv) winds are clumpy.

TTSs winds are non-stationary. The time scales for mass ejection range from a few hours (Alencar 2001; Bouvier et al. 2003; Gómez de Castro & Verdugo 2003b) to some ten years (optical jets observations, see *e.g.*, López-Martín et al. 2003) or even to some hundreds of years (molecular gas bullets, see *e.g.*, Bachiller 1996). Recent observations have established a *lower limit of about 1 hour*, precluding the association of flares with the few hours time-scale variability in RW Aur, since the characteristic decay time of flares in active stars is some few hundreds of seconds (Gómez de Castro & Verdugo 2003b). Several ejection timescales typically coexist in the same object. For instance, timescales of  $\sim 1$  h,  $\sim 5.5$  d and  $\sim 20$  yr are observed in RW Aur.

The interpretation of the profiles requires a detailed comparison with theory since the kinematics of MHD winds from rotating structures is very complex. Three basic motions overlap: rotation, acceleration along the axis, and radial expansion from the axis as shown the simple model described in Fig. 3 (Gómez de Castro & Ferro-Fontán, 2005)). Each kinematical component dominates at different locations in the outflow. Rotation is dominant close to the source of the outflow. Further out, radial expansion is the most significant component up to some height,  $z_0$ , above the disk. For

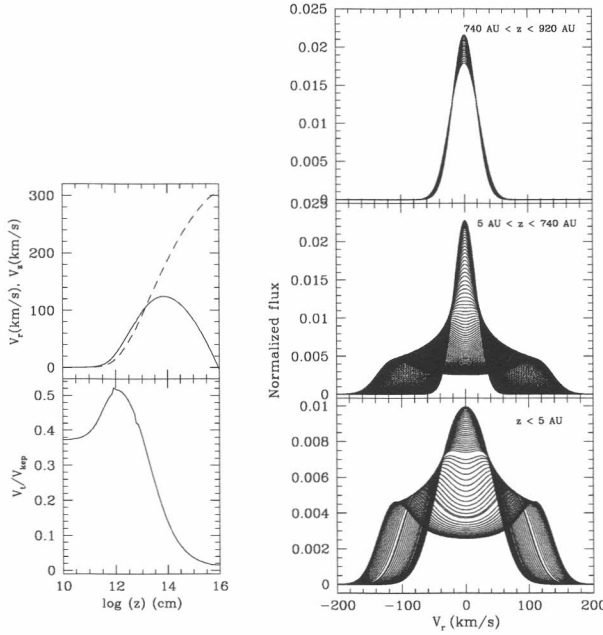


Figure 3: **Left:** Variation of the three velocity components: rotation ( $V_t$ ), radial expansion from the axis ( $V_r$ ) and axial velocity ( $V_z$ ) are represented. *Top panel:*  $V_z$  and  $V_r$  are represented with dashed and solid lines, respectively. *Bottom panel:* The ratio between  $V_t$  and the Keplerian velocity at 0.1 AU for a solar mass star ( $155 \text{ km s}^{-1}$ ) is plotted. **Right:** Disk wind kinematics as shown by the line profiles for an edge-on system. Each profile correspond to a ring of gas perpendicular to the outflow axis that is identified by its distance ( $z$ ) to the disk plane. *Bottom panel:* Line profiles with  $z < 5 \text{ AU}$  - the outflow passes from being rotationally dominated (inner broad or double peaked profile) to radial expansion dominated (double peaked profiles with peak velocity  $\sim 120 \text{ km s}^{-1}$ ). *Middle panel:* outflow passes from being radial expansion dominated to axial-acceleration dominated. *Top panel:* outflow is dominated by axial acceleration and the line broadening is basically thermal (from Gómez de Castro and Ferro-Fontán 2005).

$z > z_0$ , the dominant kinematical component is acceleration along the disk axis, *e.g.*, a collimated outflow or jet. This kinematical description is valid for the three possible types of outflows expected from these systems (see Fig. 1): stellar wind, disk wind, and outflow driven from the interface. Either centrifugal stresses or magnetic/thermal pressure are involved in the acceleration of the outflows, but it remains unclear which mechanism is dominant, whether it is universal, and how this mechanism acts when radiation pressure becomes significant as in Herbig Ae/Be stars.

### 3. Herbig Ae/Be stars

Herbig Ae/Be stars are intermediate-mass ( $2\text{--}10 M_{\odot}$ ) PMS stars that seem to be magnetized (Brown et al. 1996, Deleuil et al. 2005, Donati et al. 1997) in spite of their large masses; gravitational collapse is expected to be superalfvénic. UV-optical monitoring campaigns discovered azimuthal structures in the wind of AB Aur (Praderie et al. 1986) and clumps of very hot gas (Bouret et al. 1997) suggesting the existence of two wind components alike the observed in the solar wind:

A “slow”, dense outflow reaching terminal velocities of  $\sim 300 \text{ km s}^{-1}$ . Mass-loss rates derived from semi-empirical models are a few  $\times 10^{-8} M_{\odot} \text{ yr}^{-1}$  (Bouret & Catalá 1998; Catalá & Kunasz 1987).

A “high” velocity component made by streamers of magnetically confined gas.

Since Herbig Ae/Be stars are fast rotators, gas in the streamers is forced to corotate up to the alfvén point and shocks are expected to occur between the “slow” and “fast” components. As a result, dense azimuthal structures are formed in the corotating interaction regions (CIRs). The existence of a magnetic collimator is further supported by the detection of low-density  $\text{Ly}\alpha$  jets in HD 163296 and HD 104237 (Devine et al. 2000; Grady et al. 2004). Accretion, however, may not be the driver of the outflow. Radiatively-driven winds are able to produce collimated outflows provided there is a magnetic field (Sakurai 1985; Rotstein & Giménez de Castro 1996).

### 4. Summary

IUE and HST (with its GHRS or STIS ultraviolet instruments) and FUSE have allowed us to begin to grasp the enormous potential of the UV spectral range for the study of the physics of accretion and outflow, including the properties of the inner region of protoplanetary disks. Unfortunately, fewer than 10 TTSs were observed with spectral resolution  $\sim 50,000$  ( $6 \text{ km s}^{-1}$ ) during the lifetime of these instruments. A UV high resolution spectrograph with sensitivity 10 times that of HST/STIS would permit observations of about 100 TTSs with magnitudes 10–13 located within 160 pc of the Sun. This sensitivity limit would permit observations of much fainter and more evolved weak-line TTSs than was possible with HST/STIS.

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